

Mergers of binary stars: The ultimate heavy-ion experience

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Abstract. The mergers of black hole-neutron star binaries are calculated using a pseudo-general relativistic potential that incorporates $\mathcal{O}(v^2/c^2)^3$ post-Newtonian corrections. Both normal matter neutron stars and self-bound strange quark matter stars are considered as black hole partners. As long as the neutron stars are not too massive relative to the black hole mass, orbital decay terminates in stable mass transfer rather than an actual merger. For a normal neutron star, mass transfer results in a widening of the orbit but the stable transfer ends before the minimum neutron star mass is reached. For a strange star, mass transfer does not result in an appreciable enlargement of the orbital separation, and the stable transfer continues until the strange star essentially disappears. These differences might be observable through their respective gravitational wave signatures.

The closest analog of a high-energy heavy-ion collision in nature is the gravitational wave-induced merger of two compact objects involving at least one neutron star or strange quark matter star in a binary system. However, since such a collision would involve more than 10^{57} particles, it is vastly more energetic and would represent the ultimate heavy-ion experience. Such events have been suggested to occur frequently enough to account for some fractions of cosmological gamma-ray bursts and of r-process heavy elements [1].

In this work, we contrast the evolution of binary star mergers for two distinct cases: (1) A black hole (BH) and a (mostly) normal matter neutron star with a surface at which the pressure vanishes at vanishing baryon density. The interior of the star, however, may contain any or a combination of the many exotica such as hyperons, Bose (pion or kaon) condensate or quark matter.

(2) A BH and a self-bound star with a surface at which the pressure vanishes at a large baryon density. This case is exemplified by a strange-quark matter (SQM) star [2] with a bare quark matter surface.

Prototypes of these cases are shown as mass-radius relations in Fig. 1. Quantitative variations from these generic behaviors are caused by uncertainties in the strong interaction models (see the compendium of results in Fig. 2 of Ref. [3]), but do not lead to qualitative differences in gravitational mergers. The qualitative differences between the two classes of mass-radius relations will, however, produce significant changes in the outcomes of gravitational mergers.

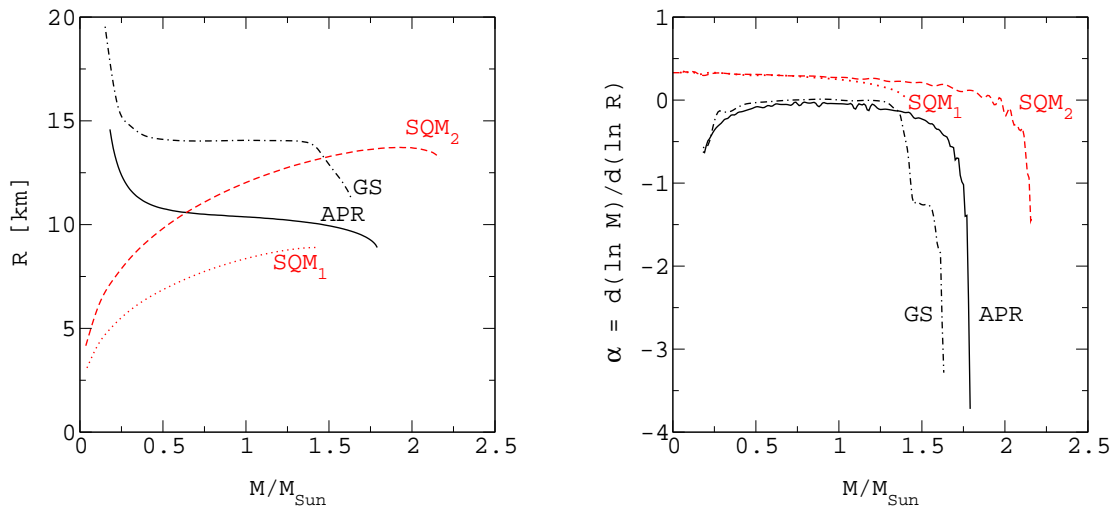


Figure 1. Radius versus mass (left panel) and its logarithmic derivative for prototype EOS's. The EOS symbols are as in Ref. [3].

A normal star and a self-bound star represent two quite different possibilities (right

panel in Fig. 1) for the quantity

$$\alpha \equiv \frac{d \ln R}{d \ln M} \begin{cases} \leq 0 & \text{for a normal neutron star (NS)} \\ \geq 0 & \text{for a self-bound SQM star} \end{cases}$$

for small to intermediate masses, where M and R are the star's mass and radius, respectively. For low mass self-bound stars, $R \propto M^{1/3}$ so that $\alpha \cong 1/3$; only for masses close to the maximum mass does α turn negative. Note that α is intimately connected with the dense matter equation of state (EOS), since there exists a one-to-one correspondence between $R(M)$ and $P(n_B)$, where P is the pressure and n_B is the baryon density. Gravitational mergers in which a compact star loses its mass (either to a companion star or to an accretion disk) during their evolution comprise a rare example in which the $R - M$ (or equivalently, the $P - n_B$) relation of a single star is sampled.

Our objective here is to explore the astrophysical consequences of the distinctive behaviors of the $R - M$ relation as they affect mergers with a black hole (see also Refs. [4, 5, 6]). In general, a gravitational merger begins with two widely-separated objects with a mutual orbit decaying via gravitational radiation reaction. When the separation becomes small, the less massive component can exceed its Roche limit and begin to lose mass to the more massive star. Typically, this can occur if the mass ratio $q = M_1/M_2$ of the two stars (M_1 is the neutron star mass) is somewhat less than unity. During mass transfer, the radius of the neutron star quickly readjusts to its new mass. If the radius increases as fast as the Roche limiting radius, mass transfer to the BH will be stable, and the inspiral will be halted and reversed due to angular momentum conservation. During stable mass transfer, the stellar radius and its Roche lobe remain coincident and mass transfer can continue until the star's mass becomes very small.

However, the loss of angular momentum and energy due to gravitational radiation reaction, as well as the extent of the Roche lobe, depend upon the gravitational potential. Until now, few merger simulations have included general relativistic corrections to the potential for $q \neq 1$. Reference [7] has evaluated the effective gravitational potential up to order $(v^2/c^2)^3$ in post-Newtonian corrections. Utilizing this potential, we have corrected the gravitational radiation reaction and the effective Roche lobe radius.

Figure 2 compares the mergers of normal and self-bound stars with a BH. Stable mass transfer ensues at the “kinks” visible in the curves for the orbital separation a , the orbital frequency ω and the scalar gravitational polarization amplitude h_+ . The normal star case is shown in the left panel; the self-bound case is shown in the right panel. Both Newtonian and pseudo-general relativistic potential cases are illustrated. In all cases, $\omega(t)$, $h_+(t)$ and $q(t) = M_1/M_2$ exhibit abrupt variations at the onset of mass transfer. Within each of the four evolutions considered, variations in the EOS do not qualitatively alter the results. The major effect of incorporating general relativistic corrections to the potential is to speed up the evolution relative to the Newtonian case. Mass transfer thus begins earlier in the pseudo-GR cases. This result does not depend upon the properties of the neutron star. GR corrections also result in a somewhat larger value for the orbital separation following the onset of mass transfer.

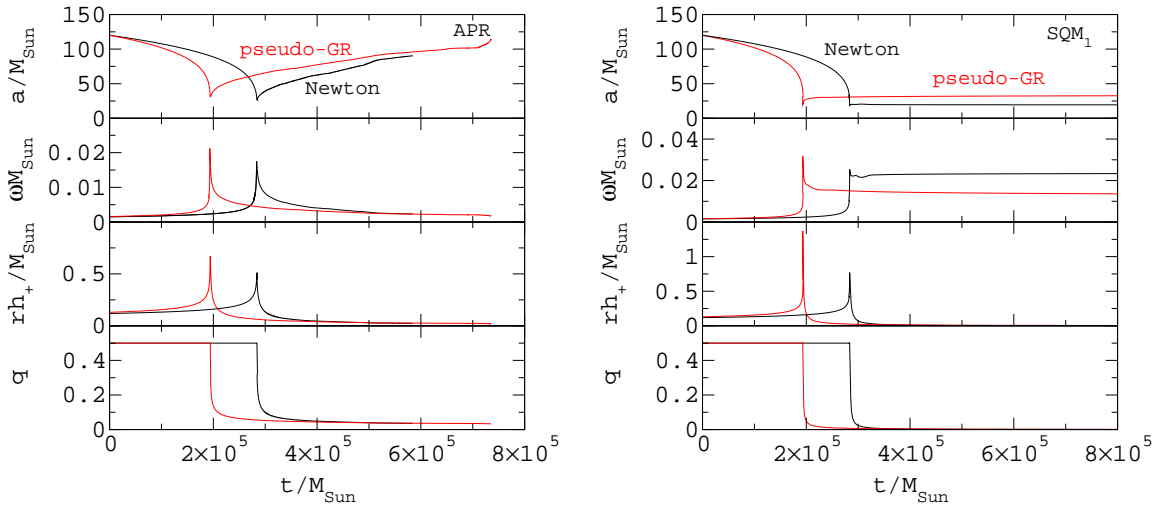


Figure 2. Evolution of mergers of a black hole and a normal star (left panel) and a black hole and an SQM star (right panel). In all cases, the initial values $M_1 = 1.33 M_\odot$ and $M_2 = 2.67 M_\odot$ were employed. The EOS symbols are as in Ref. [3]. From top to bottom: separation distance a , orbital angular frequency ω , waveform amplitude h_+ , and mass ratio q .

Larger differences are apparent between the normal and self-bound cases. The major differences are:

- the orbital separation $a(t)$ increases after mass transfer begins in the normal case, but only slightly increases and then remains constant in the self-bound case;
- reflecting the behavior of a , the orbital angular frequency $\omega(t)$ continuously decreases in the normal case, but quickly achieves a relatively constant value in the self-bound case;
- the neutron star mass M_1 approaches, but does not fall below, the minimum mass (about $0.09 M_\odot$) in the normal case, but in the self-bound case, the mass dwindles to extremely small values. In this case, the smallest mass is that of a strange quark nugget, determined in part by surface and Coulomb effects; and
- the gravitational waveform amplitude $h_+(t)$ follows the behavior of q and ω in that they rapidly decay in the self-bound case, but decay more slowly and remain finite until the end of mass transfer in the normal matter case.

Future tasks will involve the evolution of normal and self-bound star–black hole mergers including the effects of non-conservative mass transfer, tidal synchronization, the presence of accretion disks, etc. The continued evolution of normal neutron stars beyond the cessation of stable mass transfer must also be evaluated.

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